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Assessment of the Tribological Requirements of Advanced Spacecraft Mechanisms

Prepared by

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30 September 1991

Prepared for

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AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Base
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THE AEROSPACE CORPORATION
El Segundo, California



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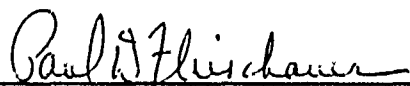
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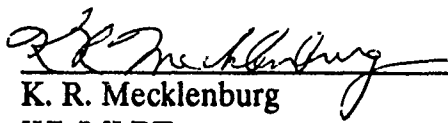

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The information in a Technical Operating Report was developed for a particular program and is not necessarily of broader technical applicability.

ABSTRACT

A survey was conducted of existing technologies for moving mechanical assemblies used in spacecraft applications. The purpose was to identify areas where future requirements for lifetimes in excess of ten years with anticipated speeds, loads, and temperatures might not be satisfied. Some specific mechanisms, such as momentum/reaction wheels, high-speed turbines, pointing and tracking mechanisms, despin mechanisms, and gimbal mechanisms, were identified as areas for potential application of existing but unused technologies. Two major problem areas identified involve boundary-regime lubrication and lubricant supply (active or passive) for long life. Areas where substantial, near-term improvements appear practical include the use of hybrid bearings, new synthetic fluid lubricants, new bearing retainer materials, and properly designed solid-film lubricants.

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I. INTRODUCTION

This assessment is concerned with problems in tribology (friction, wear, and lubrication) that can limit the useful lifetimes of critical precision mechanisms and therefore those of spacecraft systems. The prevailing attitude of most spacecraft contractors is that there are virtually no problems in tribology. After mechanical systems are designed to meet operational plans, the designer requests the lubrication "expert" to provide a lubricant to satisfy friction, wear, or lifetime requirements. Such an approach sufficed as long as performance demands were minimal, but it often led to elaborate engineering solutions or work-arounds to compensate for low-grade technology. The demands of future mechanical systems with regard to accuracy, mobility, and lifetime require that tribological demands be met in the early design phase. It will no longer be possible to assume that the appropriate oil or grease will take care of the problem.

The field of tribology encompasses all aspects of mechanical interaction in moving mechanical assemblies (MMAs). Heretofore, spacecraft systems have performed adequately (i.e., have reached lifetime requirements) with no lubricant-related or other tribology problems. However, this success was achieved because other systems (e.g., batteries, electronics, thermal and optical systems) failed before the MMAs did. At present, these other systems are becoming increasingly reliable as new technologies are incorporated. However, if the designers of complex systems fail to take into account corresponding advances in tribology, an entire system could fail as a result of limitations in tribological performance.

The objective of this assessment is, therefore, to identify mechanical components and subsystems that probably cannot meet the requirements of advanced spacecraft systems merely through the implementation of present technologies and, where possible, to recommend not only the latest technologies, but also proven -- though unused -- technologies, to meet those requirements. In some instances technologies already exist that can

be used to satisfy future requirements, but they have not been thoroughly tested or demonstrated in specific applications. In others additional research and development is required to meet the challenges.

The approach taken to assess future requirements and current capabilities was to survey satellite program offices, contractors, and other experts in the field, as well as to search the literature for published information. In addition, a review was conducted of support activities for the United States Air Force Space Systems Division (AFSSD) and the National Aeronautics and Space Administration (NASA) dealing with past problems in tribology. After a preliminary consideration of the information obtained, specific problem areas and potential solutions were identified.

The remainder of this report is organized in three sections. The first is a discussion of specific problems encountered over fifteen years of work with AFSSD and NASA. The second describes critical components and particularly difficult or demanding tribological conditions. The third concerns specific systems and recommendations for solutions to anticipated problems.

II. SPECIFIC PROBLEMS

Early work in the tribology of space systems concerned MMAs on spin-stabilized satellites. Typical designs maintained a stationary platform, e.g., for the antennas of a communication satellite, and a rotating portion that contained the electronics, batteries, and other systems. Typical examples include the Defense Satellite Communication System (DSCS II), NATO III, and a variety of commercial satellites. The most challenging problems for "spinner" satellites involved the low-torque (low-ripple) operation of despin mechanical assemblies (DMAs) and the maintenance of low torque and low electrical noise in the associated electrical interface between the rotating elements (primarily slip-ring assemblies); such mechanisms are also known as bearing and power transfer assemblies (BAPTAs). Initial anxieties arose from a fear that lubricants could be lost from the bearings by means of surface migration or evaporation [1]. Early designs included the complex labyrinth sealing of the rotating shafts to provide tortuous paths to contain oil molecules [2] (Fig. 1). Although the tribological requirements of DMA bearings are quite modest and are ideally suited for dry film lubrication, very little effort was devoted to the use of solid film lubricants in U.S. space systems, primarily because of early successes with fluids. In contrast, lead-film lubrication with sintered lead-bronze bearing retainers has been tested and used in European systems [3].

A number of laboratory life tests have been performed to analyze the performance of lubricants and hardware in DMAs, and numerous satellites have been in orbit for many years. One such life test was conducted in The Aerospace Corporation's laboratories [4] (Fig. 2), and others involving very similar test stands were conducted at contractors' facilities [5]. In typical systems bearings were of the order of 90 to 150-mm bore, had a precision of ABEC 7 or better, operated at speeds of 30 to 60 rpm, and were lubricated with an oil comparable to Vackote 36233 [6,7]. The contact stresses on the bearings were low, so that even though they operated in the mixed (elastohydrodynamic boundary) lubrication regime, the antiwear

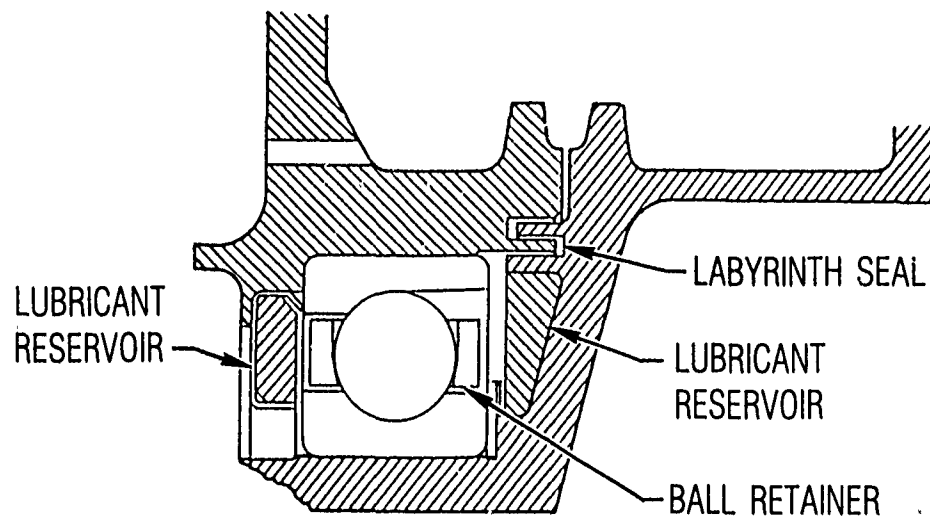


Fig. 1. Schematic of a Bearing Configuration Showing a Labyrinth Seal (from Ref. 2).

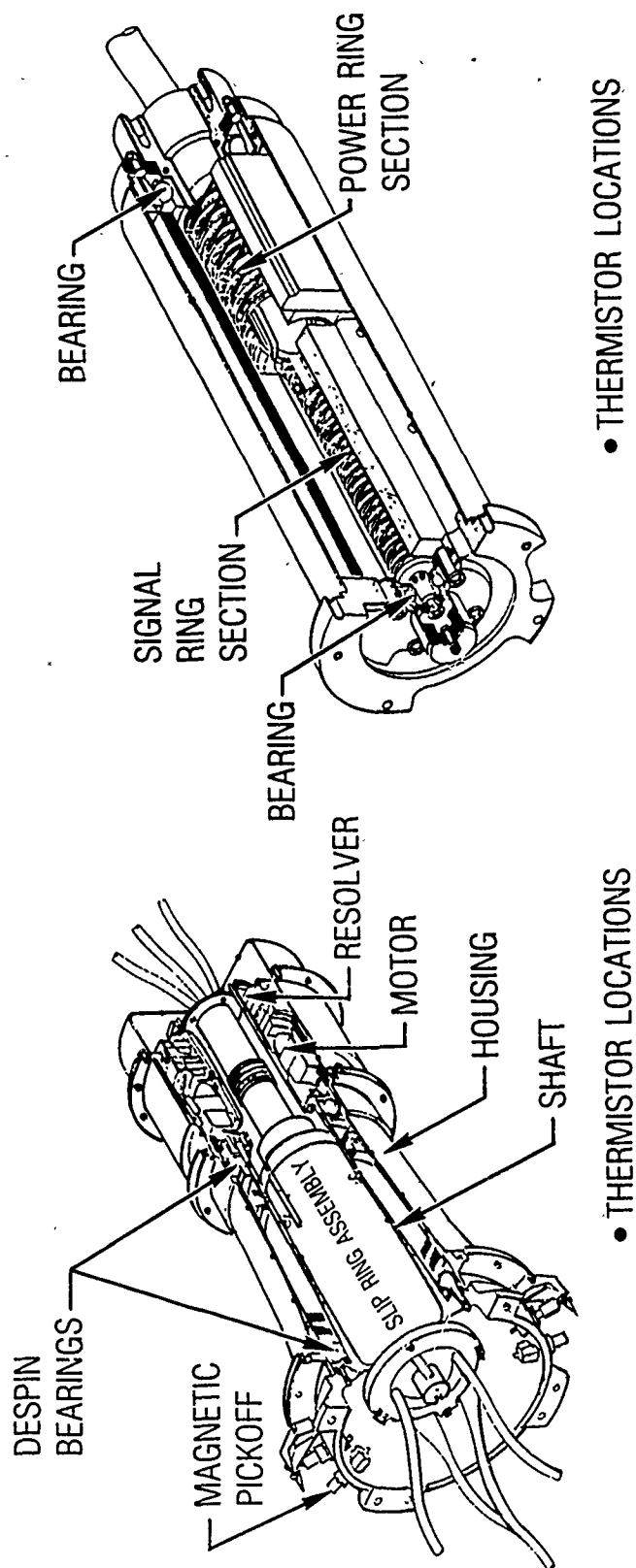


Fig. 2. Schematic of a Despin Mechanical Assembly and Slip-Ring Assembly Laboratory Life-Test Fixture (from Ref. 4).

additives in the oil prevented any significant bearing wear over six to ten years of operation. For flight systems lubricant loss rates due to evaporation were calculated, and enough oil was put into the bearings to provide a 50 to 100% margin of error.

For the most part, orbiting satellites and laboratory life-test fixtures performed very well. The Aerospace Corporation life test ran for more than seven years with no failures, while contractors' tests ran from seven to ten years with little or no bearing wear and no torque or torque noise problems. For spin-stabilized satellites, power system failures often limited life long before any tribological failures occurred.

Programs that require higher performance levels, such as improved pointing accuracies, rapid retargeting, and longer lifetimes, have generally chosen three-axis stabilization for their satellites, in which momentum or reaction wheels or control-moment gyros (CMGs) are used to achieve stability and to point and change pointing rapidly (slew) (Fig. 3). The tribology problems with three-axis systems are not only different from those in simpler systems but are also usually more complex. Medium- and high-speed (3000 to 12000 rpm) spin bearings and gimbal bearings, which operate in an oscillatory (dithering) mode and rarely make a full revolution, are of major concern for use in wheels. Also, solar-array drive mechanisms (SADMs) for maintaining the pointing of solar panels and numerous deployment mechanisms and actuators require careful design and fabrication control.

The reaction/momentum wheels for conventional communications, surveillance, and weather satellites operate under relatively benign conditions, with moderate bearing loads and torque requirements. Consequently, lifetimes of ten years have been achieved in tests and in some flight systems [8]. However, even for conventional systems, gimbals and electrical contacts have consistently been sources of anomalies and even failures. A recent survey of military tribology presents a good description of future requirements for many space systems; needs in the areas of pointing and control systems, cryocoolers, space propulsion, and longer-term space applications are described [9].

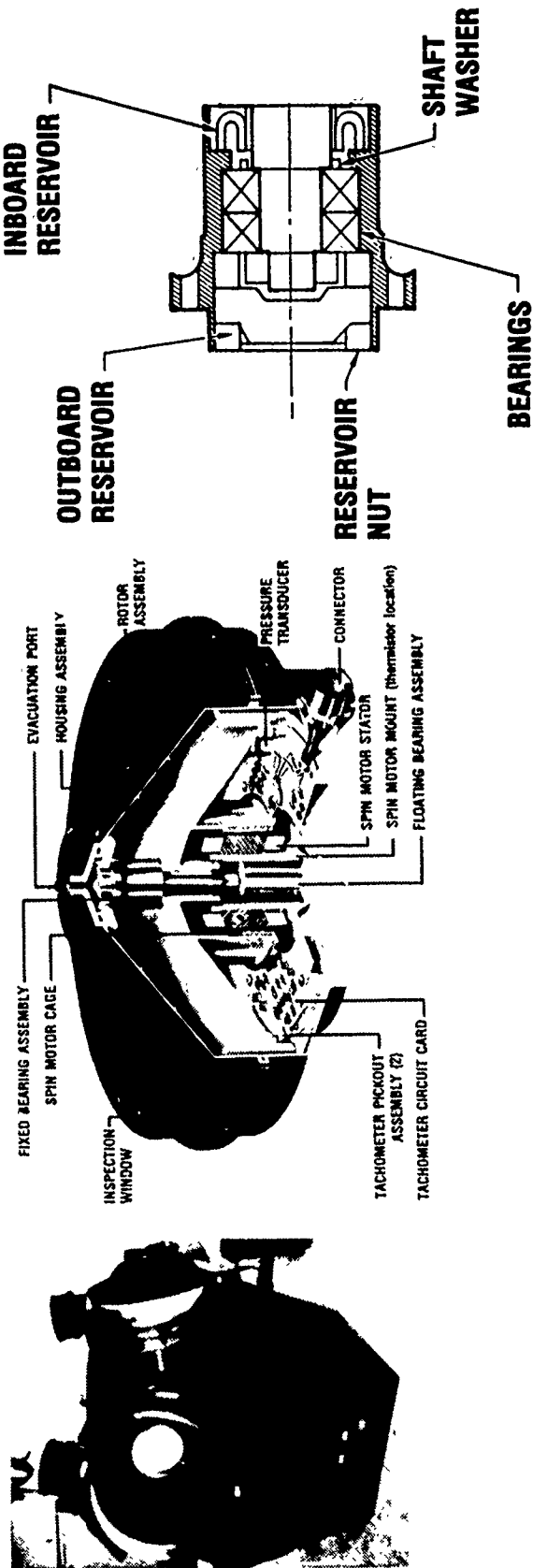


Fig. 3. Photograph, Detailed Drawing, and Schematic of Control-Moment Gyroscope and Spin Bearing Assembly (courtesy of Honeywell Inc.).

Tribology problems experienced in a variety of AFSD programs are summarized in Table I. Some problems result from inappropriate design and the failure to involve the tribologist in the design and testing phases of the programs. Examples include the potentiometer for ATP (acquisition, tracking, and pointing) control, the gear mechanism, and the telescope gimbal bearings. Such shortcomings can usually be avoided by careful planning and detailed procedures. Other problems are of a fundamental nature: the torque anomalies for spin bearings in heavily loaded momentum wheels, lubricant degradation and subsequent wear under conditions of boundary lubrication, and torque and electrical noise anomalies for slip-ring assemblies. The problems encountered typically result from an ineffective supply of lubricant to the contacting surfaces, followed by other mechanical aberrations, including bearing-retainer instabilities, excessive friction, and wear. The causes of poor lubricant supply include inadequate initial amounts, loss via transport processes, normal consumption with little or no resupply, and chemical degradation of otherwise sufficient lubricant as a result of mishandling during storage and ground testing or the improper selection of lubricant for a given application.

Table I. Tribology Problems and Their Impacts

System	Conditions	Problem	Impact
Momentum-wheel spin bearing	3600 rpm, grease pack bearings, room temp. to 100°F	Torque/temp. anomalies	Single-point mission failure, possible indicator of failure
Sensor support bearing	Preloaded ball bearings, oscillatory motion	Failure in test	> \$500K testing
Sensor launch clamp	Located inside craft thermal blanket	Seizure on launch pad	Single-point failure prohibits launch or mission failure
Harmonic drive ATP control	Very low speed, temp. < 150°F, fluorocarb. lube, boundary condition	Excessive wear, lube failure in test	Failure will degrade mission or possible mission failure - changed lubricant
Slip rings/brush contacts	MoS ₂ /Ag/C brushes on Ag rings; numerous recurrences	Excessive noise (electrical) due to moisture, corrosion	Inability to point communications antennas; reduced mission objective
Potentiometer for ATP control	Low temp. light load, fluid lube	Electr. noise, lube thickening, open circuit	Loss of pointing, reduced mission, ~\$500K testing
CMG	Oil injection on bearing land	Bearing failure, lube design wrong	Premature mission failure
CMG	Very high torque for slewing	Bearing failure	Loss of mission > \$1M test & anal.
Momentum wheel	Grease, etc.	Torque/temp. anomalies	Possible mission failure
Propellant pump gearbox	High speed	Contractor switching lubricants	Possible launch failure with new lube

Table I. Tribology Problems and Their Impacts (Cont'd.)

System	Conditions	Problem	Impact
Slip rings/ brush contacts	MoS ₂ /Ag/C brushes on Ag rings	Excessive noise due to oxidation of MoS ₂	Rework brushes and rings- delivery delay
Gear mechanism	High loads, fluorocarb. grease, boundary conditions	Lube degradation	System failure
Synchronous motor assembly	Mineral-oil-grease- packed bearings	Motor failure due to increased bearing drag	Failure would degrade mission
Momentum-wheel spin bearings	High speed, mineral-oil grease	Possible lube degradation in testing	Single-point mission failure
Inertial guidance synchronous motor bearing	High speed, mineral-oil grease	Possible chemical reac- tion between grease and iron surface during storage	Guidance failure
Harmonic drive	Low-temp. operation, fluorocarb. grease	Low-temp. viscosity of grease causes excessive torque requirement	Failure will degrade mission
Momentum-wheel, active lube system	High speed, long-life requirement	Inability to deliver adequate lube quantity	System will not meet life- time requirement
SADM	Large launch loads on MoS ₂ -lubed bearings	Test of static loads	Possible single-point failure - passed test
Gimbal bearings on telescope	Low-temp. dry (MoS ₂) lube	Tested in air, friction increase	Modified spec. to do inert gas test (passed test)

Table 1. Tribology Problems and Their Impacts (Cont'd.)

System	Conditions	Problem	Impact
Spin bearing	Large-diam, thin-cross section bearing	Humidity-induced dimensional instability of cotton-phenolic retainer	Possible target-acquisition failure, changed to metal-ball separator
Gas-bearing gyro	Alumina surfaces, stearate lube	Erratic friction on startup, uneven lube during test	Reliability problem for flight units, major rework if failure
Foil bearings for turbo machinery	High-strength alloy, CF _x -polyimide lube, temp. extremes	High-friction startup after standing	Potential system failure - inability to start turbine

III. DEMANDING TRIBOLOGICAL CONDITIONS

The problems described in Table I can be divided into the following three categories of potentially severe tribological performance:

- (1) Heavily (but variably) loaded angular-contact ball bearings, fluid lubricated, and operating under elastohydrodynamic lubrication conditions with sufficient oil supply over ten-year lifetimes.
- (2) Rolling-element bearings and gears operating under conditions of load and speed typical of boundary lubrication in space vacuum, with the ratio of lubricant film thickness to contacting surface roughness ≤ 1 .
- (3) Sliding electrical contacts in both very sensitive signal circuits and relatively high-power circuits.

Each of these scenarios presents major challenges to the tribologist and the designer.

The conditions of case (1) are typical of the spin bearings in CMGs (Fig. 3). These bearings can experience radial load cycles of $>1,000$ lb during the rapid slewing of a large sensor or the retargeting of a weapons system; in proposed surveillance missions such maneuvers would be repeated frequently over a desired ten-year lifetime. The conventional, high-precision steel bearings used in prototype CMGs have been lubricated with either mineral oil greases or super-refined mineral oils and have employed phenolic-based ball retainers. These technologies have been used for 30 to 40 years with very little refinement. Although acceptable performance levels have been achieved for present missions, demonstrated lifetimes fall far short of the ten-year goal.

Analyses of lubricants from laboratory tests [10] show the depletion of oil from grease samples taken from CMG spin-bearing cage surfaces and no depletion from samples of bulk grease. Analyses of metal parts show little evidence of wear, although some metal is found in degraded lubricant. Analytical simulations and measurements of bearing motions suggest cage instability may be involved in retainer wear and ultimately in increases in

bearing torque [11]. However, the sequence of events and conditions that lead to cage instability and failure are not yet understood. There is evidence that a constant supply of lubricant might eliminate instability and, therefore, failure [12].

Boundary lubrication conditions plague spacecraft mechanism designers and builders to the point of severe emotional distress! The problem of the loss of lubricant from the contact zone is compounded by operational requirements forbidding potential sources of contamination. Fluorocarbon oils and greases were once believed to offer a solution to this lubrication problem because of their extremely low vapor pressures and reasonably good lubricating properties for nonboundary conditions. However, testing has shown that perfluorinated lubricants do not provide for the numbers of contact cycles (bearing revolutions) required for most long-term applications, primarily because of their inability to dissolve the antiwear additives traditionally used in the base oils to minimize friction during conditions of boundary contact [13].

An even harsher set of tribological requirements is encountered for gimbal mechanisms in which, typically, ball bearings are forced to oscillate over very small arcs, or dither, and then turn to a new position and continue to dither. The gimbal system combines the severity of boundary conditions with the fretting motion of contacting surfaces. Gimbals are critical elements of most pointing mechanisms -- antennas, sensors (e.g., telescopes), and weapons platforms -- and of CMGs. Usually, performance levels are met when systems are first tested; but with time, lubricant degradation, bearing wear, or both degrade performance levels so that mission requirements no longer can be satisfied. Some of the proposed requirements of new systems (e.g., ≤ 1 - μ rad pointing accuracy with ≤ 0.25 - μ rad jitter) offer particular challenges, even for initial operation.

Slip-ring assemblies for the type of despin mechanical assembly depicted in Fig. 2 were constructed of gold- or silver-plated rings and wire wipers lubricated with the same fluid lubricants used in the bearings of the DMAs [14]. Such configurations provided good, reliable performance

but are precluded on many advanced missions because of the potential for contamination by fluid lubricants. Dry-film-lubricated systems typically consist of Ag/MoS₂/carbon brushes on silver or coin-silver rings in the United States and Ag/MoS₂/Cu brushes on silver or coin-silver rings in Europe [14,15]. Molybdenum disulfide (MoS₂)-lubricated systems can provide outstanding electromechanical performance for both signal and power circuits. However, extreme care is required to prevent excessive oxidation of the MoS₂ lubricant and the simultaneous tarnish formation that results in unacceptable electrical noise and even measurable torque increases. Many such problems with electrical noise can be traced to the fabrication and assembly practices used during the construction of the slip-ring mechanisms; but even after the mechanism is incorporated into a satellite, it is still necessary to protect the brushes from atmospheric exposure.

Dry-film-lubricated slip rings must be tested, at least in part, under the actual conditions of use (i.e., at operating rotational speeds) when electrical noise is of concern. Many tests of dry-lubricated bearings can be accelerated by increasing the speed of rotation, but for electrical contacts faster rotation can generate heat that can correct resistance anomalies. Conversely, if noise is observed in test, it is sometimes possible to eliminate it by increasing rotational speed for a brief period. Unfortunately, it is sometimes observed that such noise returns after some period of normal operation, making circuit reliability very poor.

The operation of gas bearings for gyroscopes and for turbomachinery (hydrostatic or hydrodynamic) is usually believed not to be a tribology problem. However, recent situations involving the ground testing of such systems have demonstrated that erratic friction forces between otherwise noncontacting surfaces can result in the inability to start mechanism rotation. In general, proper lubricant choice, coating procedure, and testing can provide systems that do satisfy performance requirements, but situations that would require bearing redesign can be envisioned.

IV. POTENTIAL SOLUTIONS/NEW TECHNOLOGIES

This section describes some existing materials technologies whose implementation into systems already described will probably provide for dramatic increases in performance, especially in operational lifetime. For the most part, these technologies have been demonstrated in specific space applications. However, they have not been examined for use in solving the problems described in the previous section. In the order of their ease of incorporation and demonstration, the following technologies are recommended:

- (1) The use of synthetic hydrocarbon and solid lubricants.
- (2) The coating of bearing and gear parts with hard, wear-resistant films.
- (3) The fabrication of retainers for ball bearings from new polymers other than phenolic-based materials.

Polyalphaolefin (PAO) and polyolester (PE) oils can be synthesized and blended to produce viscosity, vapor pressure, pour point, and other properties in a controlled way that will suit various needs. Vapor pressures that are as low as those of linear perfluoropolyalkylethers (PFPEs) have not been obtained, but they can be lower than those of conventional mineral oils, and the PAOs and PEs can be blended with additive packages to provide the same type of protection against wear, oxidation, and corrosion as is achieved by natural hydrocarbons [16]. Laboratory screening tests have shown that PAOs and PEs give the longest wear lifetimes in a simulated boundary-lubrication test facility [13], and bearing tests with a fixture designed to simulate the oscillatory motion of a weather scanner have shown that a PAO significantly outlasts both a silicone oil and a PFPE (see Fig. 4). There is every reason to expect that these synthetic oils can be used for the high-speed spin bearings of CMGs to provide added protection against retainer instability and wear.

Dry-film lubricants consisting of vapor-deposited thin films of lead or MoS_2 have been developed for contamination-free, very-low-friction

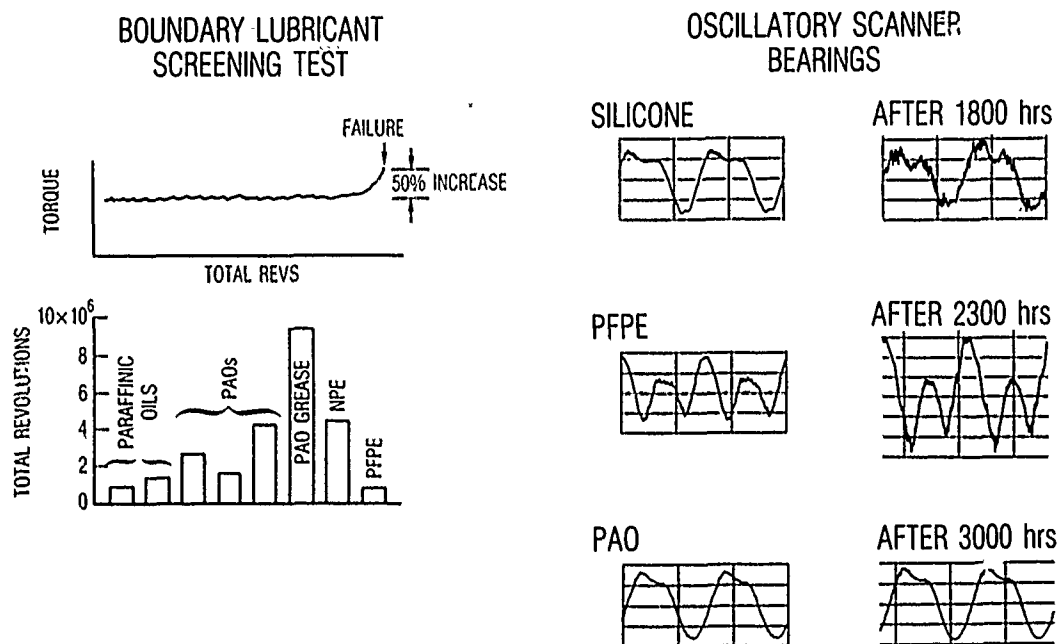


Fig. 4. Life-Test Results for Various Lubricants Investigated with a Boundary Lubricant Screening Test (left) and Oscillatory Scanner-Bearing Test (right). Silicone and PFPE failed after the indicated times, while the PAO test is still running.

applications [3,17]. The best lead films are applied by means of ion plating and are used in ball bearings to maximum effectiveness in conjunction with sintered lead/bronze retainers that act as a source for the resupply of spent film material. (See also the companion assessment of European trends in space tribology [18].) Ultralow-friction, durable films of MoS_2 are deposited by various ion-sputter deposition processes. Though used in some applications of sliding, very-low-load bearings, as well as for latching and release mechanisms, these films are still in the development phase for most ball-bearing applications [19]. There is very encouraging evidence that ion-assisted, sputter-deposited MoS_2 films can provide ultralow-friction operation even in atmospheric applications [20].

Titanium carbide (TiC)-coated bearing balls have been used in gyroscope bearings with uncoated steel raceways and superrefined mineral oil to produce operational lifetimes a factor of ten or more longer than those for uncoated balls [21]. The commercial process for coating bearing parts with TiC [22] is available in the United States, but to the authors' knowledge this process has been used only for instrument bearings of the type used in gyroscopes. Titanium nitride coatings are used only for tool steels to provide much longer service lives [23], and considerable research and development is underway to use TiN for bearings and gears [24, 25]. Tests are currently underway in our laboratories to test the performance of both gimbal and spin bearings with TiC- and TiN-coated balls. Upon the conclusion of these and other component-level tests, it is critical that results be incorporated into system testing to demonstrate the effectiveness of these technologies for space applications.

It is currently easier to select the necessary synthetic oils and hard-coated bearing parts for space applications than it is to select non-traditional bearing-retainer materials. However, polymeric materials have been developed and are used for certain applications [26]. In addition, experimental work with specially designed retainers for solid-lubricated bearings has been done [27], and numerous sacrificial-type retainer materials are available commercially [7]. Commonly used phenolic-based materials are undesirable for very long-life applications because of their

irreproducible, time-dependent oil absorption properties (Fig. 5). The data for Fig. 5 were obtained from samples that had been vacuum impregnated with oil and then allowed to soak in the oil for the times indicated. It is not surprising that such retainer material acts as a sink for oil in a bearing, rather than as a source [28]. The development of new materials having reproducible properties is imperative if reliable, very long-life bearings and MMAs are to be produced for future space missions.

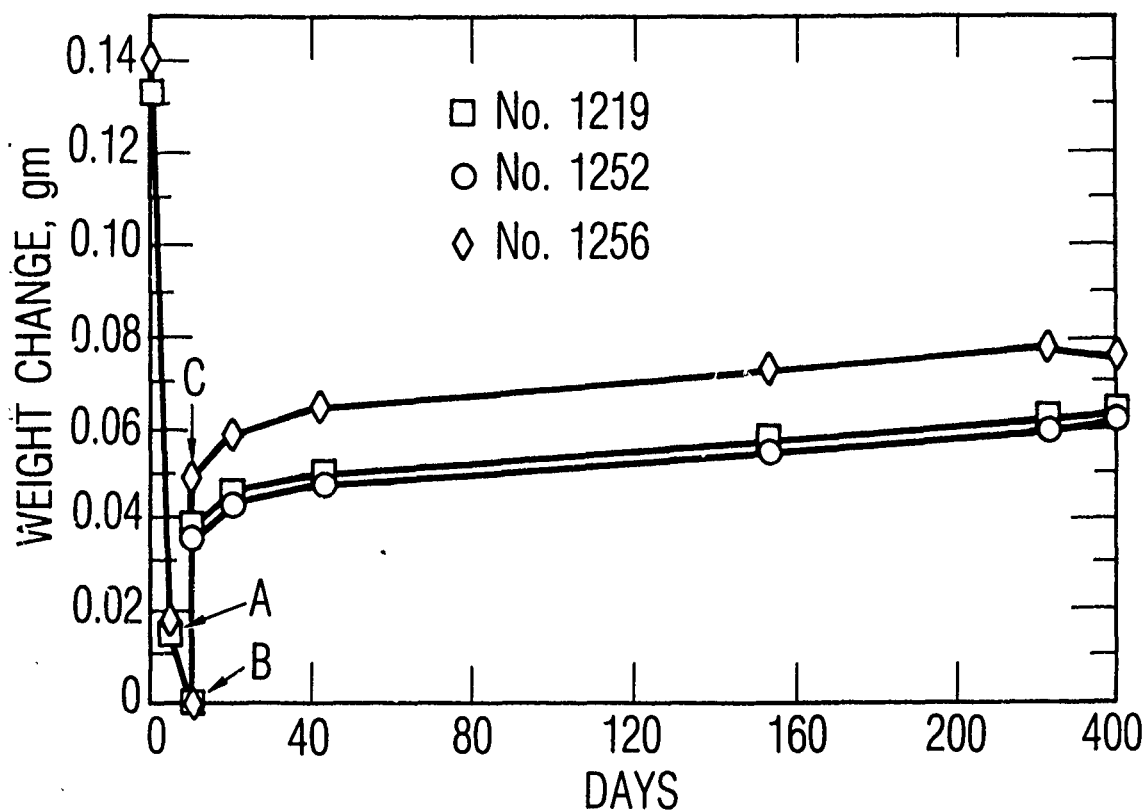


Fig. 5. Absorption of Oil by Phenolic Retainers as a Function of Time for Three Samples of Phenolic Material. (A) Vacuum bake at $\sim 100^{\circ}\text{C}$ for 24 hr. (B) Soxhlet extraction in Freon TF. (C) Vacuum impregnation with KG-80 oil. Time after point indicates storage in KG-80 oil. Initial sample weights were as follows: #1219 -- 4.2038 g, #1252 -- 4.19905 g, #1256 -- 4.20595 g.

V. CONCLUSIONS

The increased demands for pointing accuracy, targeting versatility large structures, and long lifetimes of moving mechanical systems require that very careful consideration be given to tribology in SDI and other advanced space systems. Examples of specific areas of need are the conditions of boundary lubrication, such as are produced by the dithering action of gimbal bearings; the insufficient supply of lubricant to critical contact surfaces, as in the case of spin bearings for CMGs; the need for low friction and high, constant conductivity in sliding electrical contacts; and the development of low-wear surfaces for many gear applications. Areas of existing and new materials technologies that offer the promise of solving many of these problems are hard coatings for bearing parts; synthetic hydrocarbon oils; composite retainer materials; and ultralow-friction, solid lubricant films for bearings and gears.

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